# Using Constructed Wetlands to Reduce
# **Nonpoint Source Pollution in Urban Areas**

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## Abstract

Potential pollutants carried in stormwater runoff from urban surfaces are a major component of Nonpoint Source (NPS) pollution. NPS pollution is a leading cause of reduced water quality in US rivers and lakes, and there are major efforts underway to find innovative approaches to reducing NPS pollution from a wide range of sources, In urban areas, where much of the land has existing structures, a major challenge is to find ways to retrofit built sites to reduce NPS pollution associated with stormwater runoff. One component of this may be more widespread use of constructed wetlands that have value not only in terms of water quality improvement, but also in terms of urban ecology, aesthetics and education.

We have begun a long-term monitoring program of the performance of constructed wetlands in two settings: 1) On a commercial site where surface runoff is dominated by stormwater flow from parking lots and store roofs, and, 2) On a golf course that receives considerable surface flow from adjacent commercial, residential and highway areas. Monitoring includes both continuous measurements of flow, temperature, conductivity, pH and dissolved oxygen, and automated sample collection during storm events for more complete chemical analyses. Initial results suggest that the commercial site constructed wetland acts as an efficient trap during the spring and summer for suspended sediment and some dissolved matter. During the fall and winter dormant season trap efficiencies are much lower, and in some cases negative. The golf course site constructed wetlands also function as efficient traps during the summer, and plant growth in these wetlands has been helped considerably by the regular water supply provided by golf course irrigation. Both wetland systems also provide value in terms of improved aesthetics, their use by local educators, their diverse ecological assemblages, and the public relations benefits associated with visible efforts at improved environmental management.

Replacing portions of existing parking lots with carefully designed constructed wetlands, and adding constructed wetlands to urban recreational sites (such as golf courses and parks) should be viewed as one of several elements of an integrated approach for effective retrofitting urban areas to reduce NPS pollution from stormwater runoff.

# Introduction

One of the major challenges facing urbanized areas is to find ways to improve environmental management in ways that do not involve major, costly impacts on existing infrastructure. Increasing recognition of the environmental impacts of built areas on parameters such as runoff amount and quality has increased regulatory and public pressure to develop and implement effective management practices. However, many of the best management approaches that can be integrated into the design of new developments cannot be implemented in existing built areas without prohibitive costs. Thus there is considerable interest in best management practices that can be used to retrofit urban areas for improved environmental performance.

Wetlands have the ability to store large amounts of water, reducing flooding of surrounding areas and in some cases recharging groundwater (Mitsch and Gosselink, 1993). In addition, wetlands are capable of improving runoff quality in many situations (Perry and Vanderklein, 1996) because they trap both solid and dissolved pollutants. Wetlands also can have considerable aesthetic benefits, and provide habitat for a wide range of plants and animals. Constructed wetlands are wetlands specifically designed and built for hydrologic and water quality management, as opposed to either natural wetlands or created wetlands. Created wetlands are designed and built to replace lost wetlands or to compensate for destruction of natural wetlands. Using constructed wetlands for water treatment attempts to take advantage of the benefits of wetlands without compromising natural wetland areas.

In urban areas there are unique challenges to be faced in proposing and designing constructed wetlands, Existing built areas rarely include extensive undeveloped space that can be converted to constructed wetlands. However, there are several opportunities that arise in many areas, including: 1) Making space by reducing the size of an existing parking lot; 2) Adding a constructed wetland to a redevelopment or urban renewal project; 3) Adding a constructed wetland to a park or green space; 4) Adding constructed wetlands to existing recreational facilities such as golf courses. A second major challenge in proposing constructed wetlands in built urban areas is to maintain adequate hydrology for long-term wetland survival. The extensive impervious surfaces of built areas generate large amounts of runoff during storm events, but this water is usually routed quickly away from the built area to prevent flooding. Because there is little opportunity for rainfall to infiltrate into the soil in urban areas (because most soil is covered by impervious surfaces), shallow groundwater flow is reduced. This means that wetlands in urban areas will receive far less between-storm water recharge from shallow groundwater than would be expected for a similar non-urban setting. In essence, wetlands in urban areas will experience a "flood and drought" hydrologic regime, which is poorly suited to an ecosystem that is based on extensive periods of wet conditions. One way around this problem is to look for locations where water is applied regularly to adjacent areas, in particular where extensive irrigation is used. Golf courses and lawns and gardens of major corporate complexes are potential sites where between storm irrigation might provide excess runoff and soil water drainage to adjacent constructed wetlands.

Given the potential use of constructed wetlands to improve water quality in built areas, it is important to evaluate how well wetlands function as pollutant traps in such settings. Such studies can be used to drive design improvements, and to evaluate the cost-effectiveness of using constructed wetland for NPS pollution control. Although there has been less work done in the area of stormwater constructed wetlands, in comparison to wetlands used as part of a wastewater treatment system (e.g. Hicks and Stober, 1989), limited results so far suggest that wetlands can be effective in treating stormwater for nonpoint source (NPS) pollution (Mitsch and Gosselink, 1993; Witthar, 1993; Livingston, 1989). Few data sets are available because of poor follow-up of constructed wetland performance through appropriate monitoring programs (Perry and Vanderklein, 1996). However, available studies to date and theoretical reasoning suggest that NPS pollution control is enhanced by maximizing the distance between the wetland's inlet and outlet, including deep and shallow sections in the wetland, selecting vegetation on the basis of climate and water quality and supply conditions, maximizing the ratio of treatment area to base flow, and minimizing the slope along which the water travels (Horner, *et al.,* 1994; Witthar, 1993). The idea in such a design is to model the constructed wetland after a natural wetland, which not only has the ability to slow down the flow of water (as does a detention or retention pond), but also can remove pollutants from the runoff water. The most important factor in the design and maintenance of constructed wetlands is hydrology (Mitsch and Gosselink, 1993). Without the proper water inflow and outflow, the newly created wetland will fail and be unable to accomplish its task of stormwater treatment.

## Aims and Objectives

We are monitoring the performance of urban constructed wetlands in two settings, a constructed wetland incorporated into site development for a commercial facility and a series of constructed wetlands built into a recently renovated golf course that receives runoff from an adjacent urban area. Both sites are in West Lafayette, Indiana. The goal of long-term monitoring is to provide insight into seasonal and longer-term variations in trap efficiency, both as the basis for improved scientific understanding of constructed wetland processes and controls, and to form the basis for future improvements in design.

## Study Areas

The commercial constructed wetland site occupies approximately 0.51 ha, with a water surface area of 0.26 ha and volume of 1300 $m^3$. This wetland is intended to treat the "first flush" of runoff, and so was designed to accommodate the volume of water corresponding to first half-inch of precipitation on the store's impervious surfaces (the parking lot and the rooftop). The mean depth of the constructed wetland is 0.5 m but this includes two deeper pools with a maximum depth of 1.8 m (Tatalovich, 1998). Conventional wisdom (which may not be correct) states that 90% of the annual pollutant load is transported in the runoff produced by the first 1.3 cm of precipitation (known as the first flush), and this has been shown to be true for the transport of most pollutants over impervious surfaces (Chang, 1994). At this commercial site, runoff that exceeds the first-flush equivalent is routed to a separate basin.

One motivating force behind use of a constructed wetland on this site was concern over potential impacts on a natural wetland (Celery Marsh) adjacent to the property. In addition to the constructed wetland, this site includes: elimination of a proposed auto care center, abstinence from chemical ice-clearing methods, and construction of additional ponds to treat stormwater runoff that could potentially include harmful pollutants. The constructed wetland receives runoff primarily from the 4.1 ha commercial parking lot, as well as minor additional input from an adjacent store, local access roads, and US Highway 52.

The golf course created wetlands are part of Purdue's new Kampen Golf Course and are positioned to intercept both runoff from much of the golf course and the adjacent urban area. The developed area includes two residential highways, a section of state highway, the parking lot of a motel, a gas station, and 200 residences. The water flowing through the Kampen Course eventually enters Celery Marsh, but prior to reconstruction this water flowed directly through drainage tiles and overland transport to the marsh, with no treatment. The golf course constructed wetlands serve several purposes: providing a water hazard and aesthetic component of the course, and enhancing environmental quality that can also be used in environmental education. Runoff from the urban area travels through three constructed wetlands prior to leaving the course. One particularly notable aspect of these constructed wetlands is that they have flourished even during long dry summer periods. Frequent watering of the greens and fairways, common on most courses, has the added advantage that it provides runoff and tile drainage to the wetlands throughout the summer.

## Methodology

To determine the effectiveness of each constructed wetland in trapping potential pollutants, water samplers were installed at the inlet and outlet of the commercial constructed wetland (Figure 1), and at six locations in the golf course constructed wetland complex to track the progress of water as it enters the course, moves through the wetland system, and exits to the Celery Marsh. The samplers are equipped with ISCO® Submerged Probes that measure water levels, used in conjunction either with a weir or pipe of known geometry. The sampler uses these levels and the corresponding geometry of the sampling sites to calculate the flow into and out of the wetland. Each sampler also has a YSI® 600 Multi-Parameter Water Quality Monitor that measures dissolved oxygen, conductivity, temperature, and pH. The samplers record flow and water quality parameters every five minutes and are programmed to take water samples during storm events. Storm sampling is triggered in most cases by a change in water level, and at two locations, by rainfall intensity as measured with an automatic tipping bucket rain gauge. The trigger points were determined empirically, so that inlet and outlet samplers begin to sample at approximately the same time. The sampling programs for each sampler are split into two sections. The interval of time between samples in part A of each routine is closer together than those in the corresponding part B routines, so that sampling occurs more often during the "first flush." After that, the second stage

Figure 1. Sampling equipment at a constructed wetland. The laptop computer is downloading monitoring data from the sampler, and in the foreground is a set of 24 sample bottles for storm sampling.

of each routine samples at larger intervals to guarantee samples at times coinciding with the downward slope of the hydrograph.

Overall, the design of the experiment is to track flow and water quality into and out of the constructed wetlands continuously, both during storms and between storms, for a multi-year period. This allows for determinations of storm, seasonal and multi-year trends in constructed wetland trap efficiency. Trap efficiency can be defined in a number of ways, depending on the likely application of the results. In this work we are interested in concentration trap efficiency (percentage change in potential pollutant concentration between the inlet and outlet, both maximum and average values) and load trap efficiency (percentage change in potential pollutant load between the inlet and outlet for given points in a storm, for storm totals, and seasonally and annually). Selected samples from each precipitation event are analyzed by a Purdue University laboratory for total suspended solids (TSS), hardness, total Kjeldahl nitrogen (TKN), and total phosphorus (TP). These parameters are the same as those measured for seven other local sites as part of a larger analysis of water quality in rural and urban settings. In addition to the analyses performed at the Purdue laboratory, more complete chemical scans are performed once per season on selected samples by Heritage Environmental Services in Indianapolis, Indiana. The selection of tests is based on the pollutants that might reasonably occur at each site. The reason for this more complete scan is to determine whether any potential pollutants not routinely measured at the Purdue laboratory show up at unusually high levels. Any parameters that were not detected in the Heritage samples could potentially be excluded from future testing, but those parameters considered to be problems would need to be monitored on a consistent basis in the future.

## Results and Discussion

To illustrate possible types of analyses and some major trends in the performance data, without reviewing the entire data sets available, this discussion includes three examples from the two sites. These include a complete storm record at the commercial site, between-storm sampling at the commercial site, and first-flush storm sampling at the golf course site.

### *Sample Storm at the Commercial Site*

A 0.97 cm-storm occurred on 26 October 1997, with a double peak in intensity (Figure 2). As expected, the wetland acts to damp peak flows, so discharge values at the outlet slightly lag those at the inlet and are lesser in magnitude. Water temperature in the constructed wetland inlet is high and uniform (no diurnal variations) prior to the storm (Figure 3),
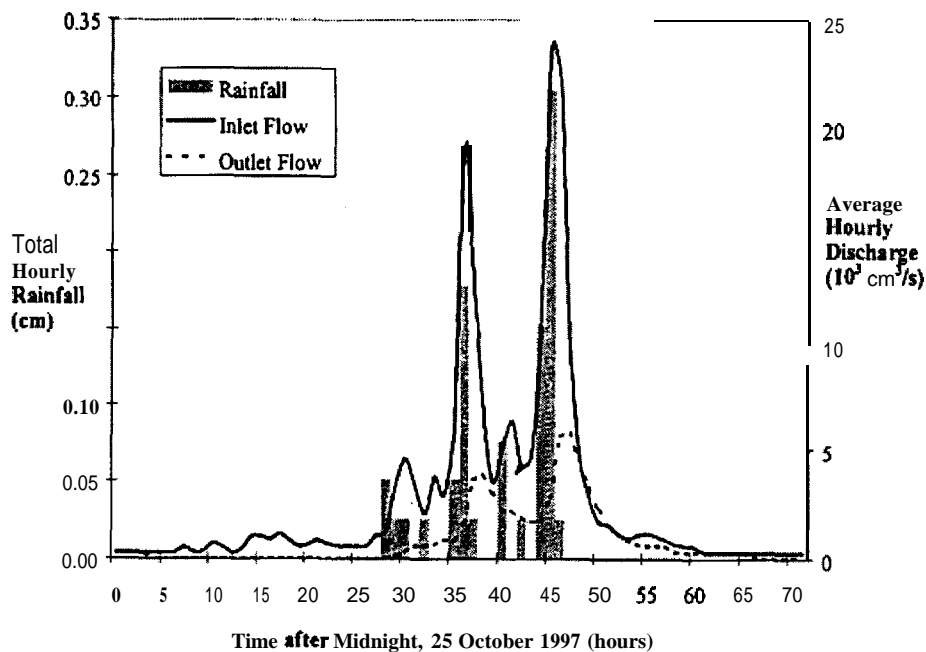
Figure 2. Rainfall and inlet and outlet runoff records for a storm event at the commercial site constructed wetland.
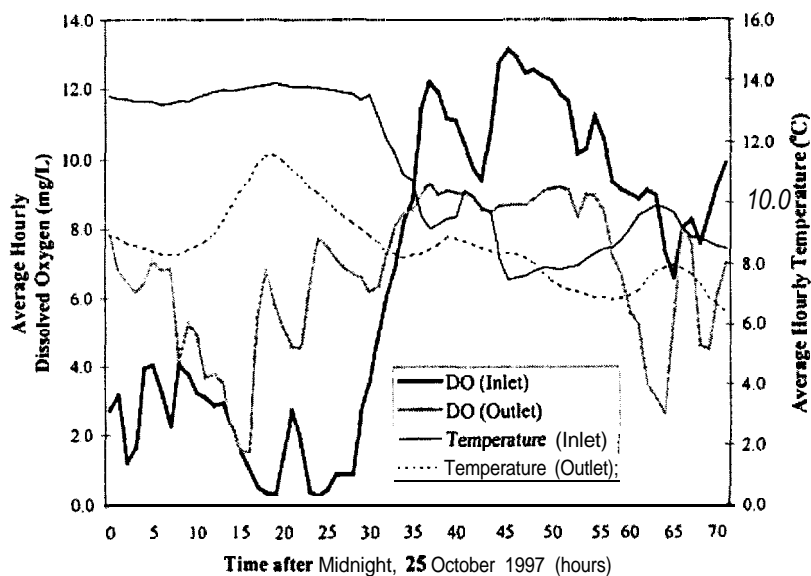


Figure 3. Dissolved oxygen and temperature records for the storm shown in Figure 1.

drops 6°C during the storm, and slowly climbs back 2°C in the 20 hours after precipitation stops. The outlet temperature shows a 4°C diurnal cycle prior to the storm, and a lower amplitude cycle after the storm. At the same time, the dissolved oxygen (DO) values climb during the storm (Figure 3). Inlet DO values vary within the 0 to 4 mg/L range before the storm, jump up to 9 to 13 mg/L during the storm, and fall during the 24 hours following the storm event. The outlet DO varies from 1 to 8 mg/L prior to the storm, is very stable between 8 and 9 mg/L during the storm, and has strong variations from 3 to 9 mg/L post-storm. High DO values during the storm are due to the increased mixing of the water, which causes oxygen to be introduced to the wetland, as well as the addition of "new" water that is higher in oxygen to the stagnant water.
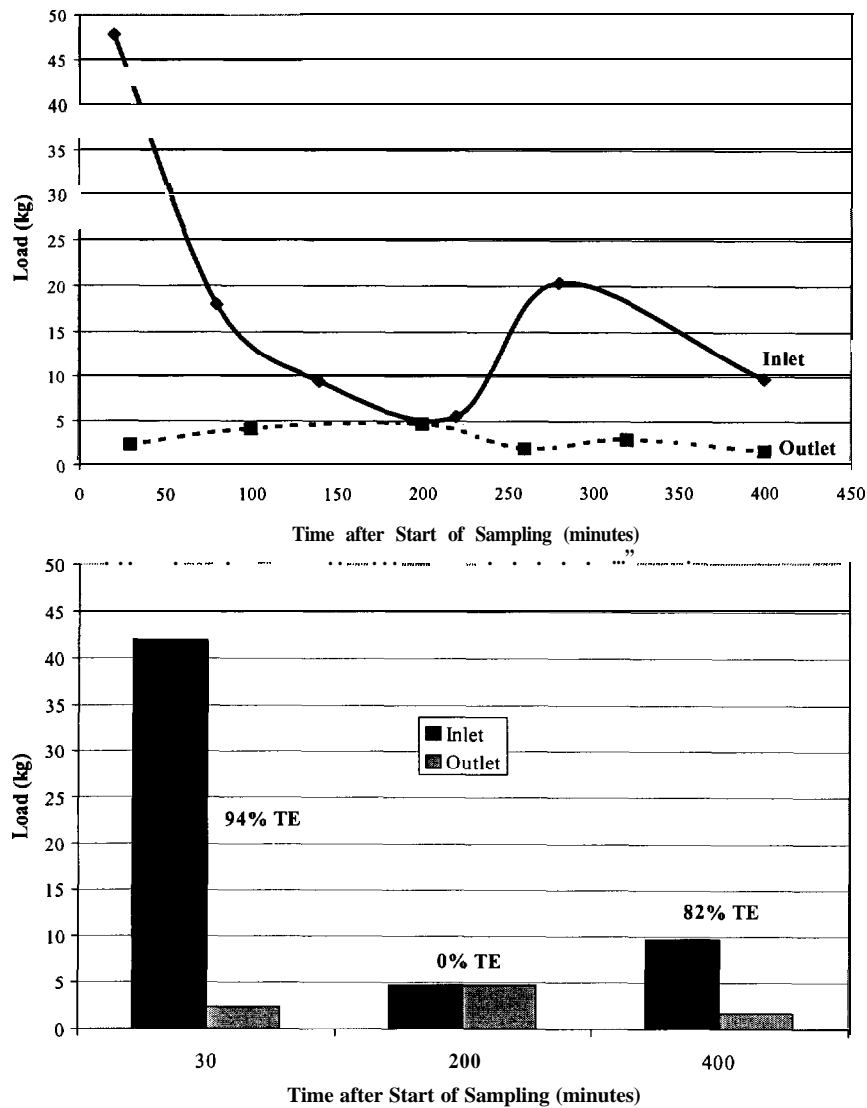
**Figure** 4. Total suspended sediment load for the storm shown in Figure 1 (upper), and calculated trap efficiency (TE) if only grab sampling had been used (lower). The actual load TE for the storm was 84%.

Initially, hardness data from the 26 October 1997 storm showed much higher values for the outlet than the inlet. This discrepancy relates to the movement of water through the wetland. Soon after the start of a storm, water begins to flow over the weir at the inlet and inlet sampling begins. This new runoff from the site has a low hardness, reflecting the naturally low hardness of rainwater. At the outlet, high hardness values show that the water initially being sampled is not new inlet water being displaced from the wetland; rather it is water that was stored in the concrete outlet box prior to the storm. Hardness values at the outlet fall throughout the storm, showing that hardness is lower in the wetland than in the

concrete outlet box. Because hard water occurs when concentrations of $Ca^{2+}$ and $Mg^{2+}$ are high (Zumdahl, 1989), the concrete surroundings themselves can add to the hardness of the water. Ninety-five percent of all concrete used is made from Portland cement, which is prepared using finely ground limestone (Mindess and Young, 1981). The cement is made into concrete using admixtures such as calcium chloride. Also, the interaction of the surface water with groundwater, which in this geographic location is very hard due to infiltrating rainwater that dissolves the calcite-rich till from limestone in the region, can add to the hardness of the water in the wetland (Davis and Cornwell, 1991).

The hardness data suggest that the outlet record probably does not include water that enters and exits the wetland during the same storm. Other studies (e.g. Bhaduri, et al., 1997) have shown through chemical load distributions that the inflow and outflow from a basin are actually two different water masses, except in extreme storm events. The only way that the same water could appear at the inlet and outlet during the same storm would be if the inflow sheeted over the water in the basin, arriving at the outlet without significantly mixing with the water stored in the wetland prior to the storm; or if the storm produced enough water to completely displace the volume of water in the wetland.

Total suspended solids (TSS) concentration data and flow values for the storm are used to calculate TSS loading values, which depict the effect of the basin in reducing the overall sediment load. Total loads depict the actual physical amount of sediment entering the wetland and are important for planning activities such as dredging. TSS load values for the inlet are larger than the outlet (Figure 4). The inlet values start high, dip down, and then increase again. This indicates that the initial runoff has "first flush" (high load) characteristics, and then the load input rate decreases. A second, lower peak later in the storm could be the result of the later pulse of higher rainfall intensity (Figure 2). The values of TSS at the outlet remain fairly uniform throughout the storm. The initial value presumably represents between-storm ambient TSS loading in standing water in the wetland. During the storm, the increase in flow creates more turbulence, which can stir up some of the bed sediment, slightly increasing the TSS concentration and, therefore, the load. More importantly, though, the outlet values are lower than those for the inlet; thus there is a net decrease in TSS loading from the inlet to the outlet for this particular storm. In one sense, this traditional approach is a valid efficiency measure because the water going out is compared to that going into the wetland, but in another sense it is a skewed picture because the new inlet water is being compared with "old" outlet water that arrived in the basin during a previous storm (Bhaduri, et *al.,* 1997).

Multiple storm sequence sampling will provide a better view of overall trap efficiency (TE) than a single storm, just as a complete storm record is better than a grab sample. Standard grab samples do not always lead to accurate trap efficiency calculations (Figure 4). If one sample were taken each from the inlet and the outlet at exactly same time, the data could show a very high trap efficiency (30 minutes), no trap efficiency (200 minutes), or a fairly high trap efficiency (400 minutes). The overall load TE for this analysis was 84%. This is one of the reasons that this particular study samples several times after the start of a storm -- to bridge the gap between standard grab samples and actual events within the wetland. Continuous monitoring provides a more complete record of the constructed wetland's activity, more accurately depicting the trap efficiency of the wetland. From conductivity data, during the monitoring period, 137 kg of dissolved load entered the basin, and 59 kg left the basin, for a total dissolved solids (TDS) load TE over the storm of 57%. Further analysis of many storms can be used to determine an overall trap efficiency over longer periods of time. This type of analysis could be used to determine the effects of different storm intensities, seasonal variations, and increased urbanization in the area.

### *Detailed Chemical Scan at the Commercial Site: Between Storm Conditions*

Samples for a detailed chemical scan were taken on 17 December 1997 using the sampler's grab sampling mechanism. At this time, there had not been a precipitation event in a couple of weeks, so these samples represent between-storm conditions in the wetland. Although these samples were tested for many possible pollutants, only a few were detected (Table 1).

Parameters which show reductions between the inlet and the outlet were chloride, sulfate, ammonia nitrogen, calcium, magnesium, sodium, silicon, strontium, and total dissolved solids (TDS). For instance, chloride levels fell from 210 to 160 mg/L, calcium levels fell from 95 to 54 mg/L, and strontium levels fell from 0.16 mg/L to below the detection level of 0.10

Table 1. Detailed chemical scan of the commercial site constructed wetland. All values are mg/L.

| Parameter | Inlet | Outlet | Detection Limit |
|---|---|---|---|
| Chloride | 210 | 160 | *2.5* |
| Sulfate | 49 | *37* | 1.3 |
| Nitrogen, Nitrate-Nitrite | 0.12 | 0.11 | 0.01 |
| Nitrogen, Ammonia | 0.21 | 0.14 | 0.12 |
| *Chemical Oxygen Demand* | *18* | *28* | *10* |
| *Aluminum* | *BDL* | *1.3* | *0.10* |
| Calcium | 95 | *54* | 0.10 |
| *Iron* | *0.33* | *1.7* | 0.70 |
| *Potassium* | *2.5* | *2.7* | *0.10* |
| Magnesium | *28* | 15 | 0.10 |
| Manganese | *0.32* | *0.24* | 0.10 |
| Sodium | 110 | *85* | 0.10 |
| Silicon | 5.1 | *3.0* | 0.10 |
| Strontium | 0.16 | BDL | 0.10 |
| Total *Organic Carbon* | *BDL* | *4.2* | 7.0 |
| *Total Phosphorus* | *BDL* | *0.10* | *0.03* |
| Dissolved Solids | *720* | *490* | 10 |
| *Total Suspended Solids* | *4* | *13* | 1 |

Notes: Italicized parameters are those which have an outlet value > inlet value.
BDL = below detection limit

mg/L. Also, TDS levels fell from 720 to 490 mg/L. When compared to the values calculated using conductivity data from the sampler, these values are slightly higher than the values calculated for the 26 October 1997 storm event. The maximum TDS values calculated for the inlet and the outlet were, respectively, 568 and 365 mg/L, with average values around 337 and 263 mg/L. The higher between-storm values could be a result of the ability of sediments to dissolve in the wetland waters. Reductions in values between the inlet and the outlet indicate removal of certain pollutants within the wetland and also suggest that at the beginning of a storm, the outlet values will be lower than those of water near the inlet. Because of this, the best TE should be at the start of a storm, which is shown in the 26 October 1997 storm chemical data.

Not all of the detectable parameters were lower at the outlet than at the inlet. The ones that were actually larger at the outlet than at the inlet were: chemical oxygen demand (COD), aluminum, iron, potassium, total organic carbon (TOC), total phosphorus (TP), and total suspended solids (TSS). The increase in TSS is interesting, and may be the cause of increases in adsorbed pollutants. This could be attributable to the lack of growth of plants in the middle of December. Plants slow flow within the wetland, allowing sediments in the water to settle, and plants have the ability to take into their roots pollutants carried by the sediments (Pond, 1995). Because of this, as the plants die, they may release the sediments and pollutants trapped earlier in the year, as well as releasing products of the decay of the organic matter. Aluminum, iron, potassium, and phosphorus could have been attached to these sediments, especially the finer particles. Findings such as these agree with previous studies that noted a distinct reduction in the performance of stormwater wetlands in winter months (Oberts, 1994; Ferlow, 1993). Not only does plant death have an effect, but also the formation of ice on the water surface can scour the margins and resuspend the sediments and the pollutants that they carry (Oberts, 1994).

### Detailed Chemical Scan at the Golf Course Site

First flush samples were collected for detailed chemical analysis during the first pulse of runoff from a storm in November 1998 and a second storm in June 1999 (Table 2). In November 1998, 14 water quality parameters declined in terms of a comparison between the urban input (Site 1) and the golf course output (Site 6). Four water quality parameters improved between the urban input and the water exiting the course during the same storm. This suggests that the constructed wetlands were not working well soon after initial construction, during the late fall. However, key parameters such as ammonia and nitrate-nitrite nitrogen and pesticide levels were either decreased as the watercirculated through the golf course wetlands or were not detectable at either sampling site.

A distinctly different pattern of results is apparent in the June 1999 sampling (Table 2). Fifteen water quality parameters improved between the urban input and the water exiting the course, and only 4 parameters declined. This suggests that the golf course's created wetland system is functioning well to improve the water quality in the late spring when wetland plants have become established. Two parameters of particular interest for a golf course are nitrate-nitrite N and ammonia-N, which were undetectable in water exiting the course, but at 2.1 and 31 ppm, respectively, in water flowing onto the course.

Table 2.    Detailed chemical scan of the golf course site constructed wetland, selected parameters.    All values are mg/L.

| | | November 1998 | | | June 1999 | | |
| | | Site 1 | Site 6 | | Site 1 | Site 6 | |
| Parameter | Detection limit | Urban runoff | Created wetland outlet | increase/ decrease | Urban runoff | Created wetland outlet | increase/ decrease |
|---|---|---|---|---|---|---|---|
| Simazine | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Atrazine | 0.10 | BDL | BDL | BDL | 0.1 | BDL | -91%' |
| Oil and Grease | 5 | BDL | BDL | BDL | BDL | BDL | BDL |
| Chloride | 2.5 | 8.6 | 22 | +156% | 32 | 20 | -38% |
| Sulfate | 2.5 | 11 | 55 | +400% | 18 | 31 | +72% |
| Nitrogen nitrate-nitrite | 0.01 | 1.1 | 0.06 | -95% | 2.1 | BDL | -100%" |
| Ammonia nitrogen | 0.12 | 0.23 | BDL | -52%' | 31 | BDL | -100%* |
| Chem. 0, Demand | 10 | 40 | 37 | -8% | 480 | 25 | -95% |
| Mercury | 0.0002 | BDL | BDL | B D L | BDL | BDL | BDL |
| Total Organic Carbon | | 8.2 | 10 | +22% | 240 | 1.6 | -99% |
| Phosphorus | 0.03 | 0.19 | 0.17 | -11% | 0.32 | 0.08 | -75% |
| Dissolved Solids | 10 | 91 | 270 | +197% | 240 | 220 | -8% |
| Suspended Solids | 1 | 17 | 290 | +1606% | 8 | 2 | -75% |
| Silver | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Aluminum | 0.10 | 0.31 | 5.8 | +1771% | 1.8 | 0.16 | -91% |
| Arsenic | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Calcium | 0.10 | 29 | 61 | +110% | 40 | 34 | -15% |
| Cadmium | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Chromium | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Copper | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Iron | 0.10 | 0.51 | 4.7 | +822% | 1.6 | 0.26 | -84% |
| Potassium | 0.10 | 2.3 | 7.8 | +239% | 2.2 | 0.37 | -83% |
| Magnesium | 0.10 | 7.1 | 24 | +238% | 9.9 | 28 | +183% |
| Manganese | 0.10 | BDL | 0.21 | +133% | 0.28 | BDL | -64% |
| Molybdenum | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Sodium | 0.10 | 4.5 | 6.8 | +51% | 6.5 | 8.7 | +34% |
| Nickel | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Lead | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Selenium | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Silicon | 0.10 | 2 | 14 | +600% | 2.0 | 4.8 | +140% |
| Tin | 0.10 | BDL | BDL | BDL | BDL | BDL | BDL |
| Titanium | 0.10 | BDL | 0.14 | +56%* | BDL | BDL | BDL |
| Zinc | 0.10 | BDL | BDL | BDL | 0.38 | BDL | -74%' |

BDL = Below Detection Limit
. where contaminant was BDL, the detection limit was used for % increase/decrease calculations

No unusually high levels of any of a wide array of potential pollutants, including pesticides and metals, were detected at the golf course sampling sites. However, atrazine was detected in water exiting the neighborhood and entering the golf course (Site 1). Surprisingly, even from the urban runoff there was no measurable oil and grease. It is reassuring to note that heavy metals of concern, such as mercury and lead, are below detection limits in all samples.

## Conclusions

Constructed wetlands can potentially be used to improve NPS pollution management in urban areas. Although finding space for constructed wetlands can be a challenge in developed areas, these management tools can be incorporated into the design of new or renovated commercial and industrial facilities. In some cases, they can be added to recreational

facilities such as parks and golf courses. In each of these cases, good initial design and attention to continued water supply for long-term wetland survival is critical.

The constructed wetland monitoring program in West Lafayette, Indiana, includes both commercial and golf course constructed wetlands. Selected results presented here illustrate the complexity of developing a program to evaluate performance of such wetland systems. Traditional grab sampling can provide misleading results compared to continuous sampling, and it is clear that apparent trap efficiency varies both within storms as well as between seasons. The type of complete picture of constructed wetland performance that is needed to improve design and enhance understanding of chemical and biological processes in constructed wetlands can be approached by continuous monitoring through several years. Initial data suggest that the constructed wetlands studied here are generally performing well to reduce loads and concentrations of a range of urban NPS pollutants, particularly during spring and summer storm events after wetland vegetation has become established. However there is also a strong indication that trap efficiencies are much lower, and in some cases negative, during winter months. The implications of this depend on the context provided by the receiving area.

Constructed wetlands also provide important benefits beyond water quality control. They provide aesthetic diversity in urban settings, they represent islands of habitat types that are generally absent or underrepresented in older developed areas, and they provide important local educational resources in urban areas. Overall, constructed wetlands should be considered as a potential element of urban retrofit projects, if there are situations where water supply is available to maintain wetland hydrology.

## Acknowledgments

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